

Sensor Selection and Data Validation for Reliable Integrated System Health Management

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Abstract

For new access to space systems with challenging mission requirements, effective implementation of integrated system health management (ISHM) must be available early in the program to support the design of systems that are safe, reliable, highly autonomous. Early ISHM availability is also needed to promote design for affordable operations; increased knowledge of functional health provided by ISHM supports construction of more efficient operations infrastructure. Lack of early ISHM inclusion in the system design process could result in retrofitting health management systems to augment and expand operational and safety requirements; thereby increasing program cost and risk due to increased instrumentation and computational complexity. Having the right sensors generating the required data to perform condition assessment, such as fault detection and isolation, with a high degree of confidence is critical to reliable operation of ISHM. Also, the data being generated by the sensors needs to be qualified to ensure that the assessments made by the ISHM is not based on faulty data. NASA Glenn Research Center has been developing technologies for sensor selection and data validation as part of the FDDR (Fault Detection, Diagnosis, and Response) element of the Upper Stage project of the Ares 1 launch vehicle development. This presentation will provide an overview of the GRC approach to sensor selection and data quality validation and will present recent results from applications that are representative of the complexity of propulsion systems for access to space vehicles. A brief overview of the sensor selection and data quality validation approaches is provided below.

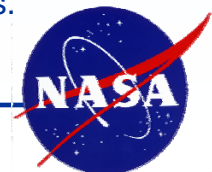
The NASA GRC developed Systematic Sensor Selection Strategy (S4) is a model-based procedure for systematically and quantitatively selecting an optimal sensor suite to provide overall health assessment of a host system. S4 can be logically partitioned into three major subdivisions: the knowledge base, the down-select iteration, and the final selection analysis. The knowledge base required for productive use of S4 consists of system design information and heritage experience together with a focus on components with health implications. The sensor suite down-selection is an iterative process for identifying a group of sensors that provide good fault detection and isolation for targeted fault scenarios. In the final selection analysis, a statistical evaluation algorithm provides the final robustness test for each down-selected sensor suite.

NASA GRC has developed an approach to sensor data qualification that applies empirical relationships, threshold detection techniques, and Bayesian belief theory to a network of sensors related by physics (i.e., analytical redundancy) in order to identify the failure of a given sensor within the network. This data quality validation approach extends the state-of-the-art, from red-lines and reasonableness checks that flag a sensor after it fails, to include analytical redundancy-based methods that can identify a sensor in the process of failing. The focus of this effort is on understanding the proper application of analytical redundancy-based data qualification methods for onboard use in monitoring Upper Stage sensors.

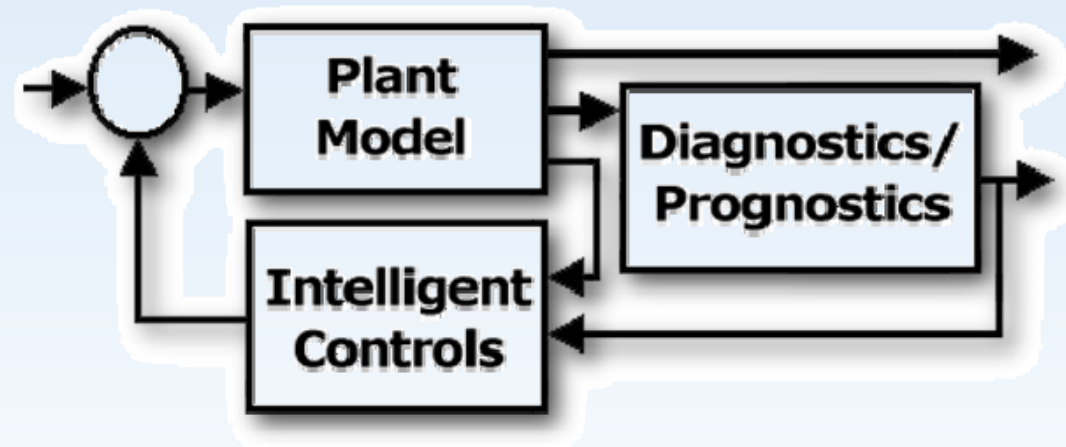
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Sensor Selection and Data Validation for Reliable Integrated System Health Management



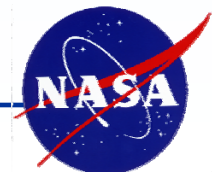
Dr. Sanjay Garg and Mr. Kevin J. Melcher
Amy Chicatelli, Chris Fulton, Bill Maul, Shane Sowers, Ed Wong
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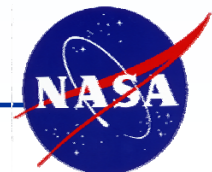
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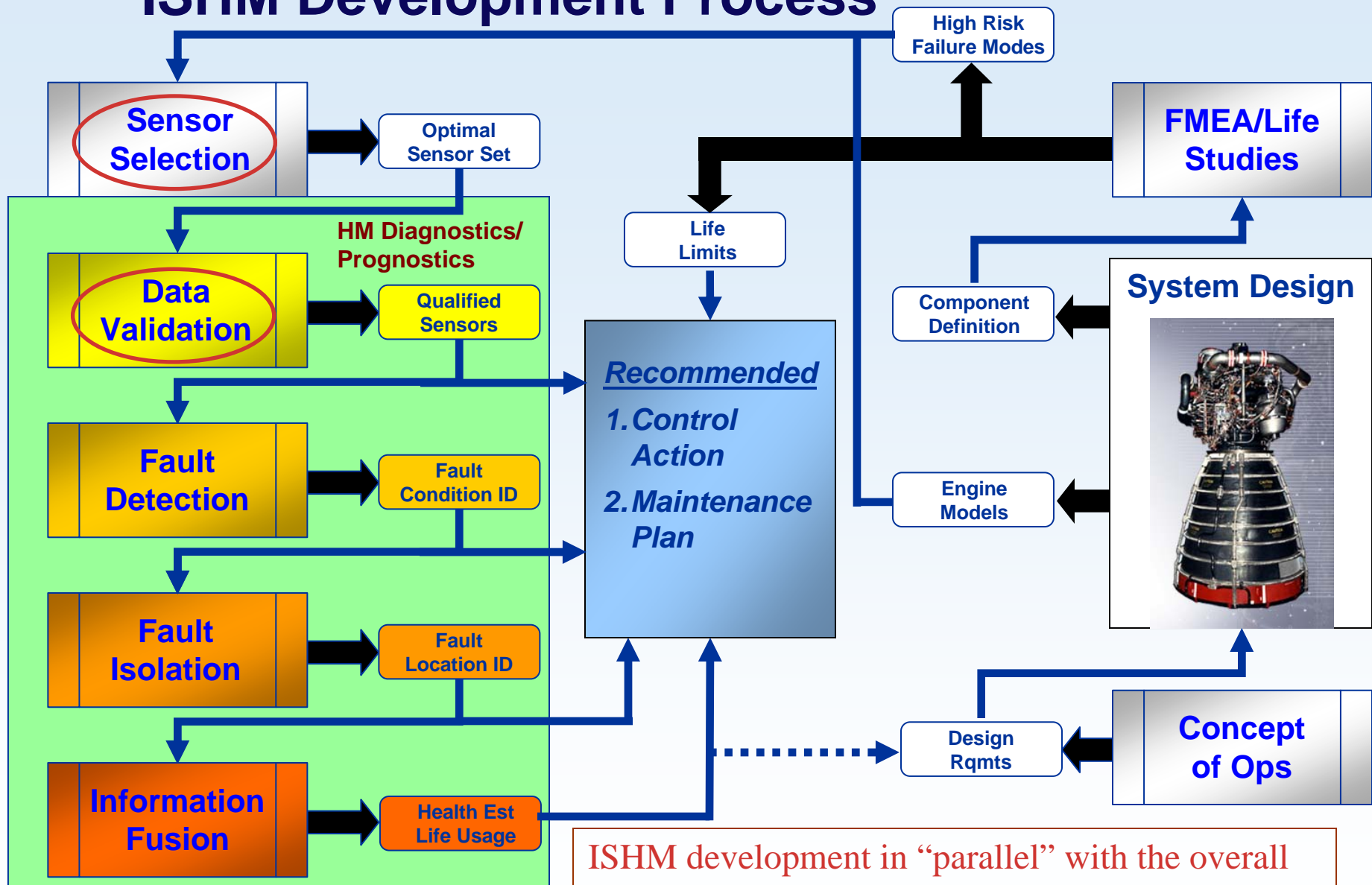


Outline

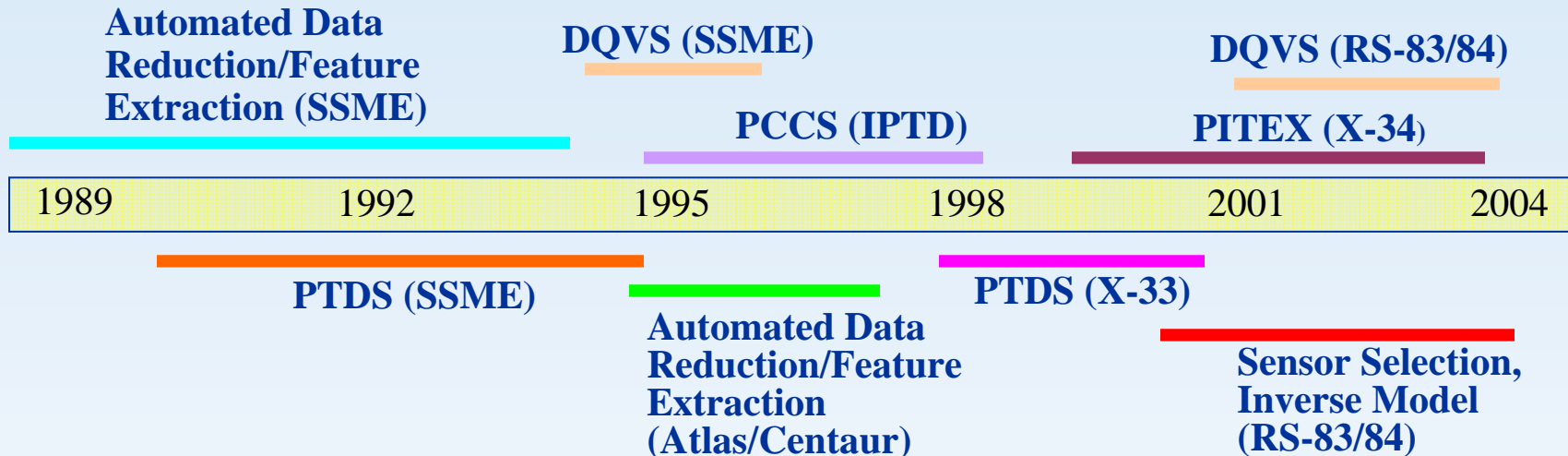
- ISHM Framework
 - GRC Historical Experience in Space Propulsion HM
 - Current Activities
- Systematic Sensor Selection Approach (S4)
 - Description and example application
- Sensor Data Qualification System
 - Description, applications to date, status and products
- Conclusions
- References and CDB Overview



ISHM Development Process



Access to Space: Propulsion HM Technology Development at GRC – Historical Perspective

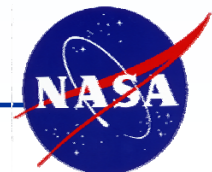


- **Automated Data Reduction / Feature Extraction – SSME and Atlas/Centaur, and Post Test Diagnostics System (PTDS) for SSME and X-33**
 - Significantly reduced time to analyze test data from weeks to days
- **Data Quality Validation System – SSME and RS-83/84**
 - Demonstrated feasibility of analytical redundancy based sensor validation
- **Propulsion IVHM Technology Experiment (PITEX) – X34**
 - Demonstrated real-time fault detection for complex propulsion system
- **Propulsion Check Out and Control System (PCCS) for Integrated Propulsion Technology Demonstrator (IPTD)**
- **Inverse Model based Sensor Selection – RS-83/84**
 - Capability to optimize sensor suite for fault detection and isolation

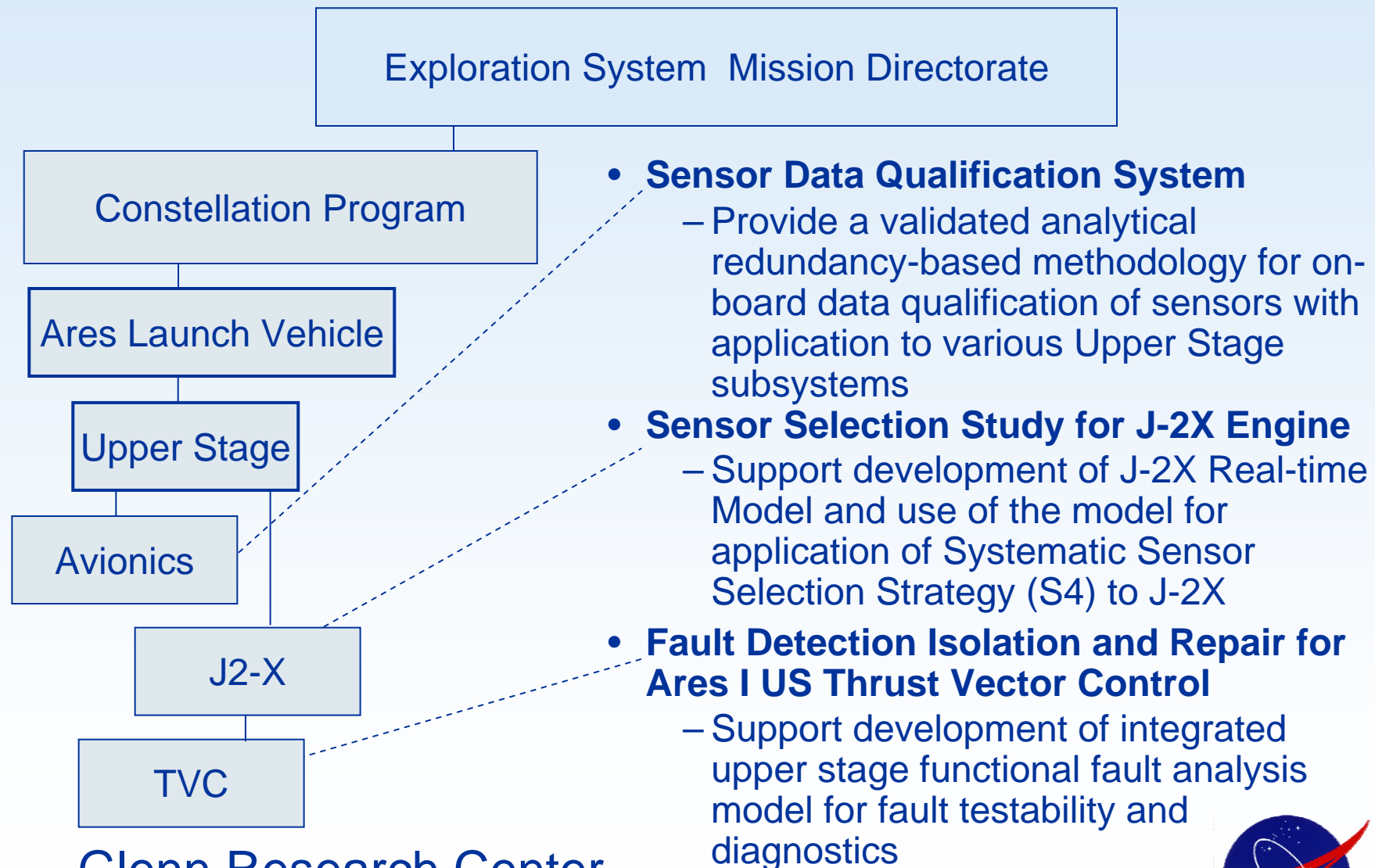
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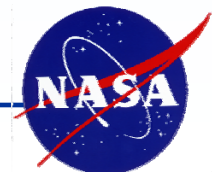
Current Propulsion System HM Activities in NASA Exploration Systems Programs



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Sensor Selection Approach

- **Current Sensor Selection Process:**

- Ad Hoc Heuristic Process - Domain Groups Polled for Required Sensors
- Sensors Selected Focused on Control Requirements and Performance Assessment, Rather Than Health Monitoring and Management
- Competing Requirements Difficult to Resolve (e.g. Cost vs. Safety)

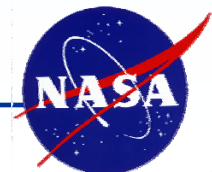
- **Desired Attributes of a Systematic Approach:**

- Justifiable, Creditable Selection and Evaluation of the Sensor Suite Relative to the Diagnostic Requirements
 - Incorporate Capability to Provide Trade Studies Between Fault Detection and Sensor Costs
 - Flexible to Incorporate the Best System Design Information Available
 - Applicable to Multiple Types of Systems (e.g. Propulsion, Electrical, Hydraulic, etc)

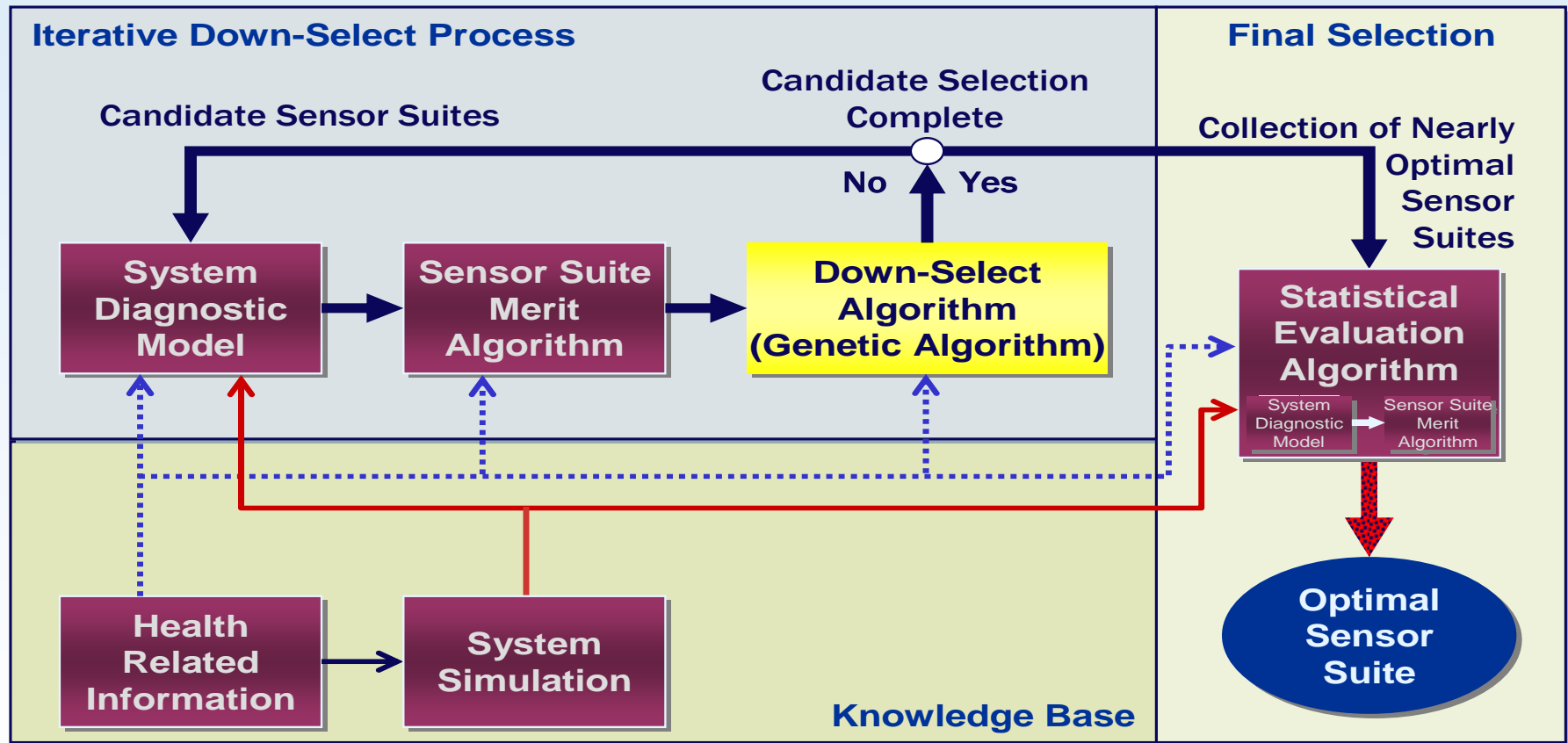
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Systematic Sensor Selection Strategy (S4) Architecture

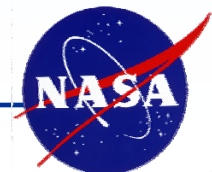


■ Application Specific ■ Non-application specific

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S4 Merit Function

$$Merit = U_S * P_{FD} * P_{PEN}$$

Utility Cost: Incorporates relative weighting values between the sensors, such as cost, weight, power requirements, etc.

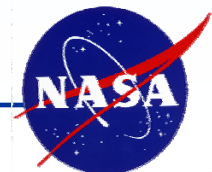
Diagnosability Performance Factor: Weighted linear combination of the total distance values for each of the tested fault scenarios

Penalty Term: User defined term used to establish a desired goal of the sensor network

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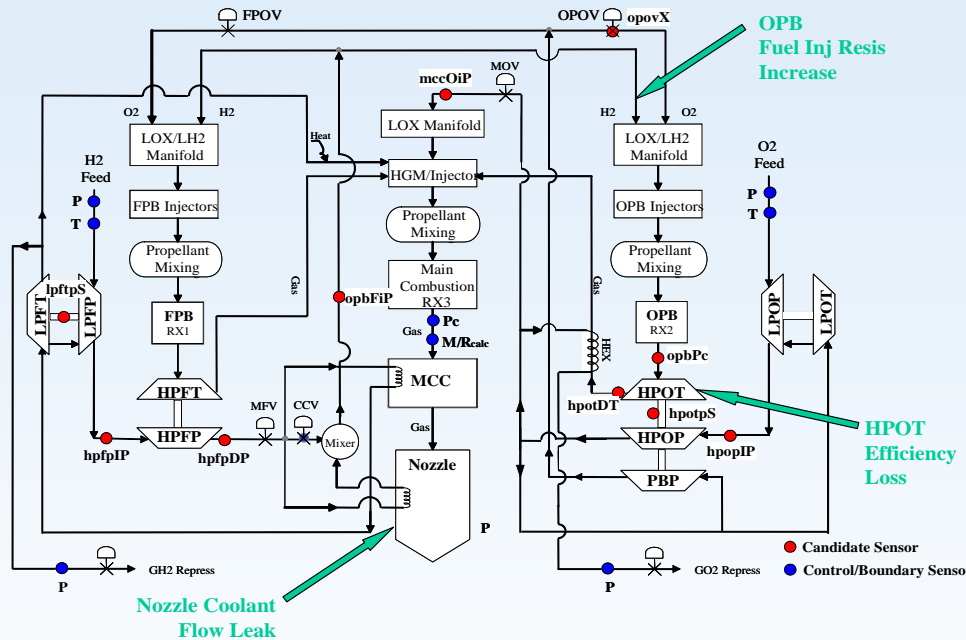
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Example S4 Application

Space Shuttle Main Engine (SSME)



Candidate Measurements

Variable	Sensor Description
hpfpDP	HPFP Discharge Pressure
hpfpIP	HPFP Inlet Pressure
lpftpS	LPFTP Speed
hpopIP	HPOP Inlet Pressure
hpotpS	HPOTP Speed
opbPc	OPB Chamber Pressure
opovX	OPOV Actuator Position
mccOiP	MCC OX Injector Pressure
opbFiP	OPB Fuel Supply Duct Inlet Pressure
hpotDT	HPOT Discharge Temperature

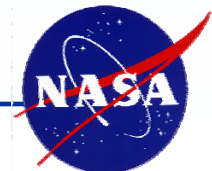
Failure Cases

- Nozzle Coolant Flow Leak
- High Pressure Oxidizer Turbopump Efficiency Loss
- Oxidizer Preburner Fuel Injector Resistance Increase

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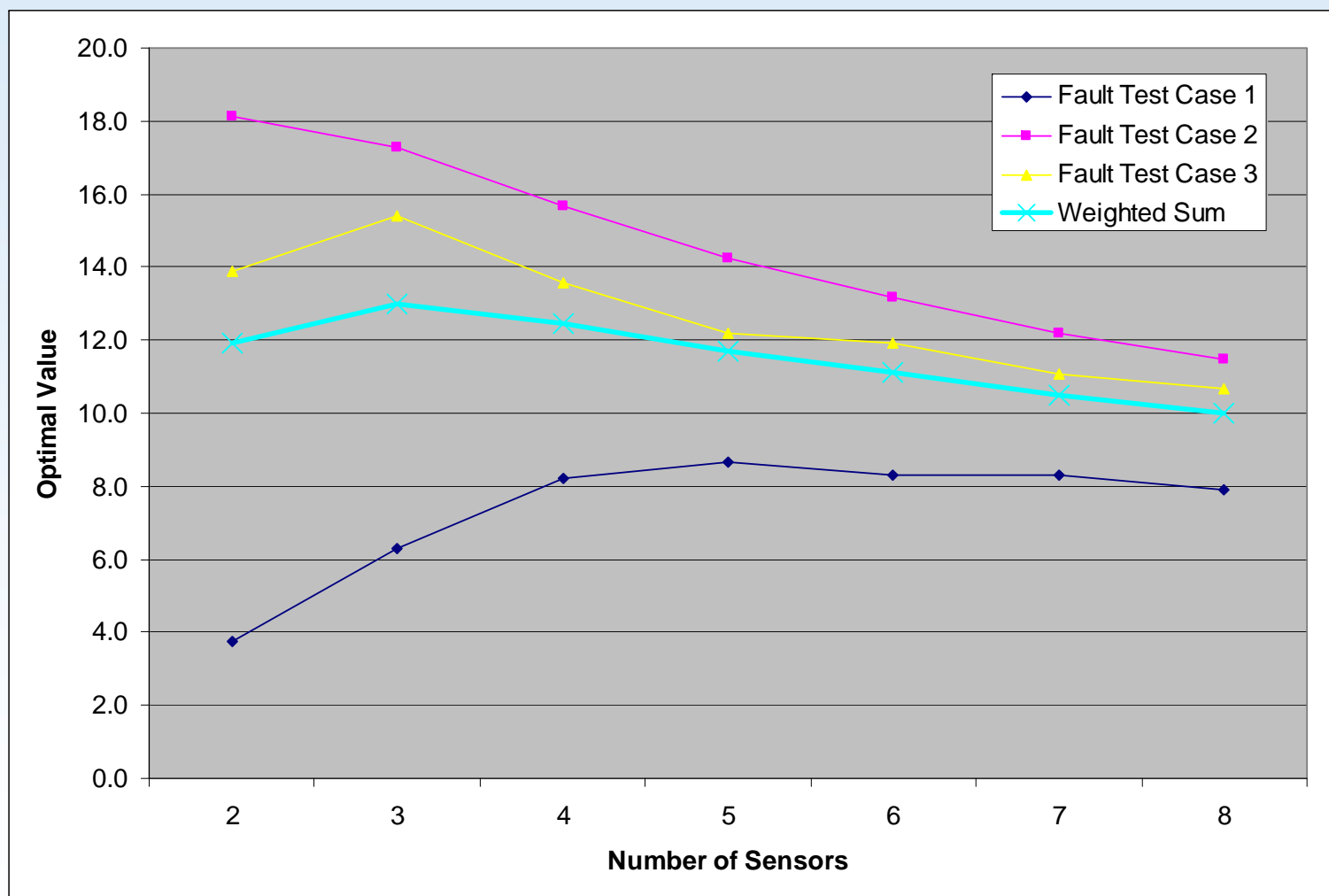
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S4 Application - SSME

Optimal Merit Value Trend



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S4 Application - SSME

Results:

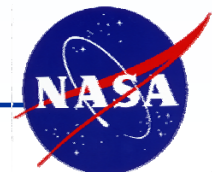
- Identified which Sensors are required to be retained at a minimum to support fault diagnostics requirements and which sensors provided no diagnostic support

Sensor Target	hpfpDP	hpfpIP	lpftpS	hpopIP	hpotpS	opbPc	opovX	mccOiP	opbFiP	hpotDT
1						X				X
2						X				X
3	X					X				X
4	X				X	X				X
5	X				X	X		X		X
6	X		X		X	X		X		X
7	X		X	X	X	X		X		X
8	X	X	X	X	X	X		X		X
9	X	X	X	X	X	X		X		X
10	X	X	X	X	X	X		X		X

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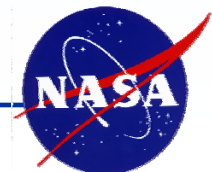
Ongoing S4 Applications

- J-2X Fault detection system development: Current activities are directed toward populating the knowledge base of the S4 framework
 - Determining fault modes of interest
 - Selecting the pool of candidate sensors
 - Establishing fault diagnostic philosophy
 - Assisting in the refinement of engine failure simulations
- Optimal sensor selection for aircraft engine gas path diagnostics
 - Framework established to apply S4 and preliminary studies completed showing diagnostic benefits of using advanced sensors
 - Provides guidance on investing resources in sensor development
- Further development of S4 ongoing to incorporate broader combinations of evaluation metrics (Sensor Reliabilities, Diagnostic Timeliness, etc.)

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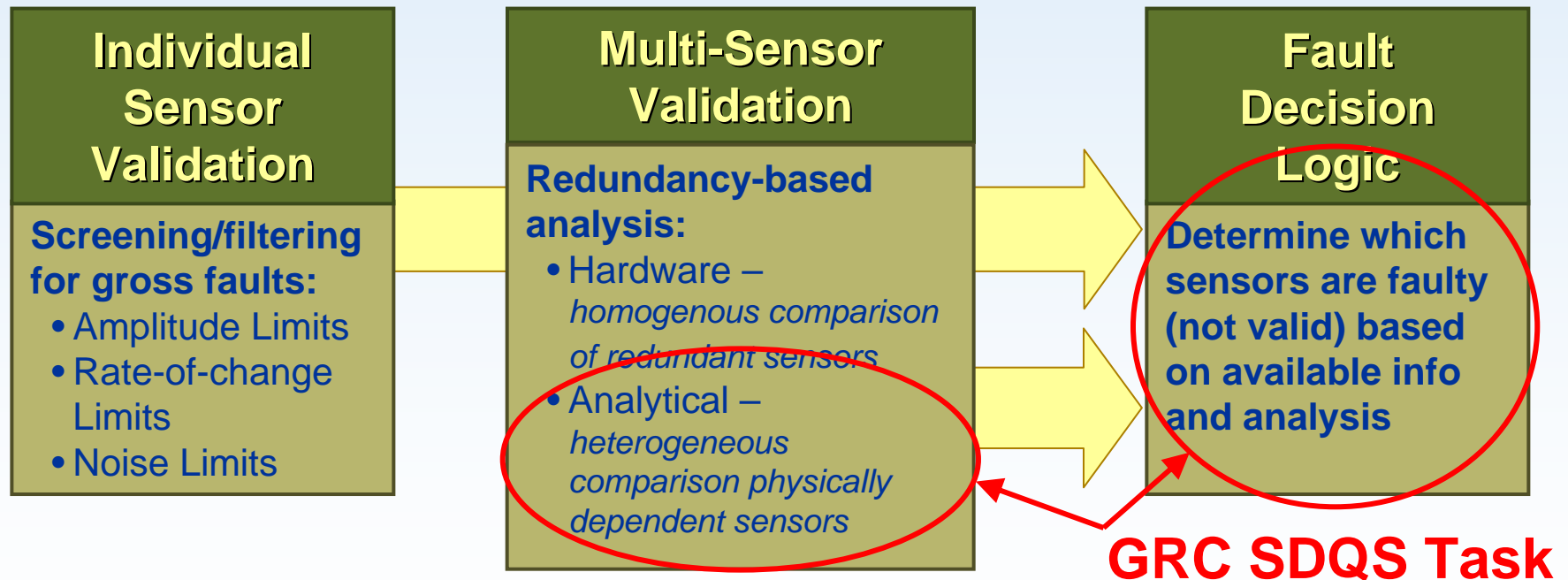
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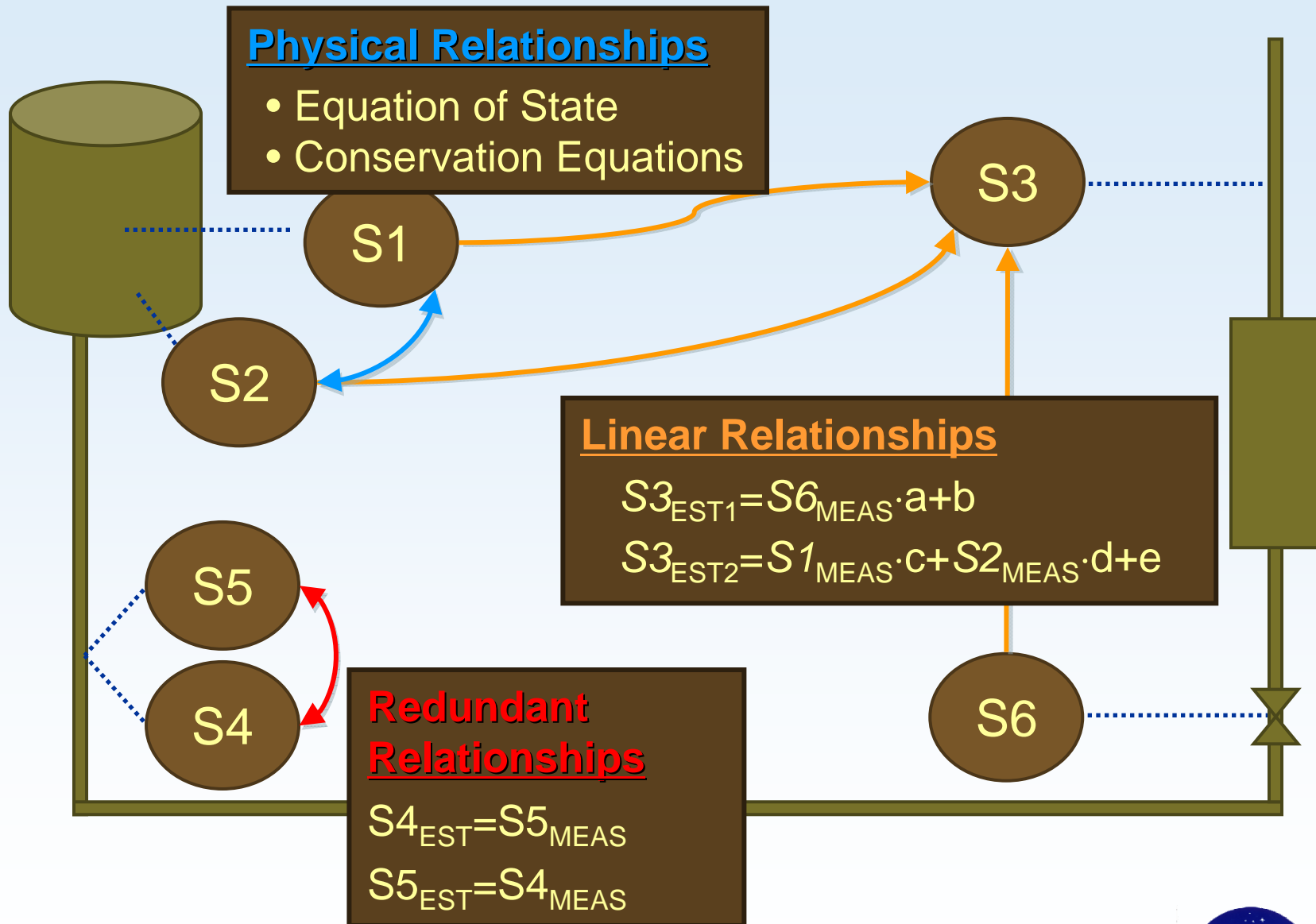


Sensor Data Qualification

- Uses mathematical approach to analyze measurement data and identify information that does not represent the true state of the system.
- Identifies faulty sensors so that they are not used for critical functions
- Can be characterized by three stages:



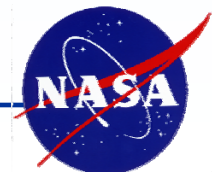
Use of Analytical Redundancy for SDQS



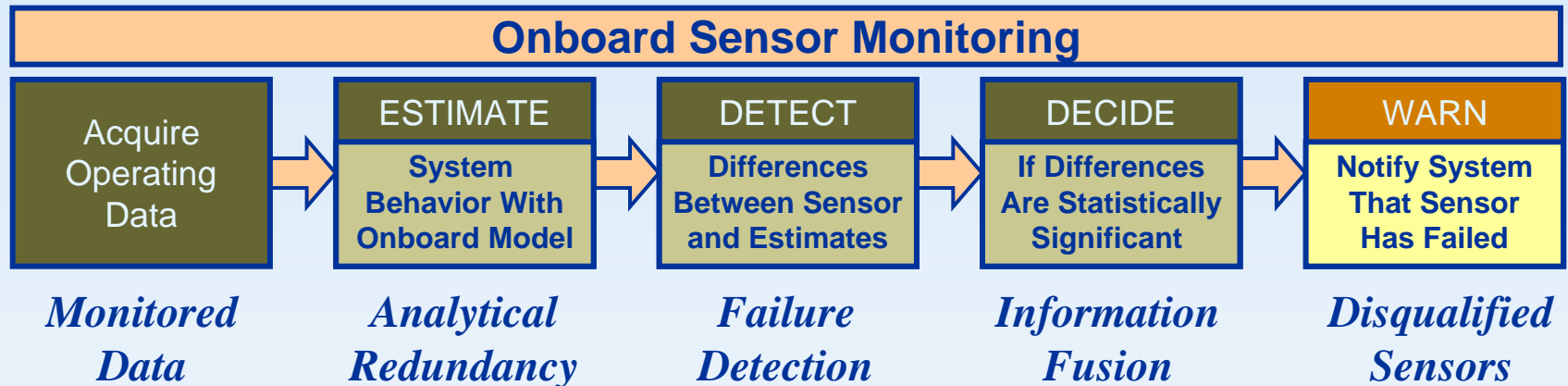
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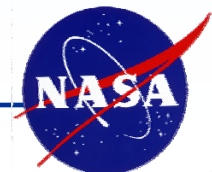
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Sensor Data Qualification Process

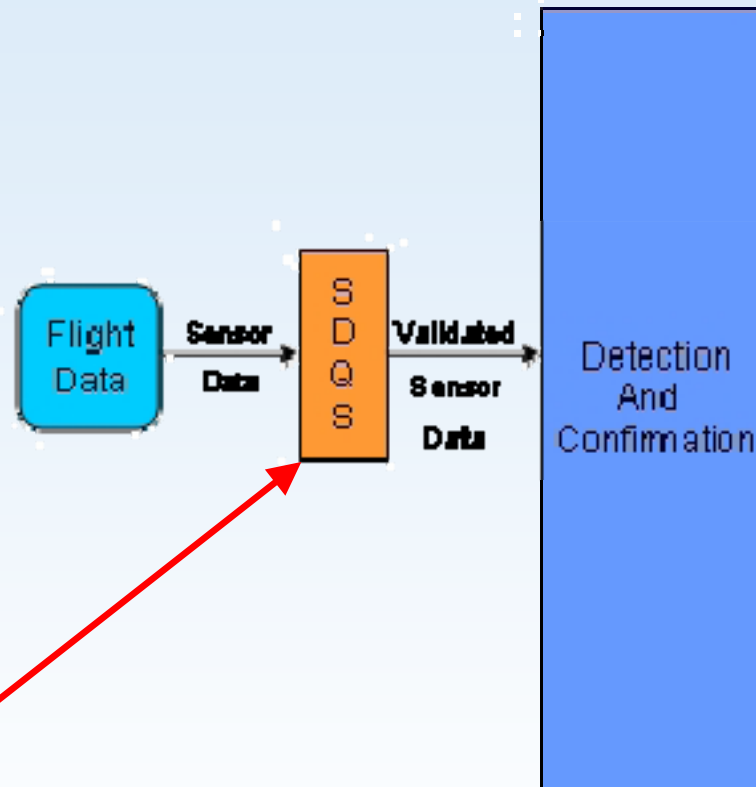


- **Estimate** sensor outputs using known relationships (models) between sensors in a redundancy group
- **Detect** breakdown of relationships within the redundancy group
- **Decide** whether or not a sensor has failed based on number and frequency of failed relationships
- **Warn** user that sensor fault has occurred



SDQS and the Ares I US Abort system

Ares I Upper Stage Abort Failure Detection and Confirmation

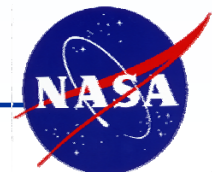


SDQS is GRC Contribution to Ares I Upper Stage Abort System

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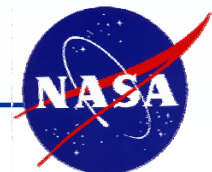
SDQS Products to Date

- Software Design & Implementation Studies
 - Demonstrates that SDQS can be implemented within resource guidelines: Lines of Code, Memory Requirements, Execution Time
 - Different architectures
- Proof-of-Concept Demonstrations
 - Power Distribution Unit Test-bed; Cryogenic Test Rig (real-time data playback); High-pressure Valve Characterization Test-bed (real-time hardware/software) *[in progress]*
 - Developed Portable Health Algorithms Test (PHALT) System for rapid prototyping and real-time execution of SDQS
- SDQS Algorithm Description Document
 - Provides implementation details for 19 algorithms
 - For each algorithm, provides: description, where to use, technology status, benefits, limitations and assumptions, flow chart, mathematical description of algorithm etc.

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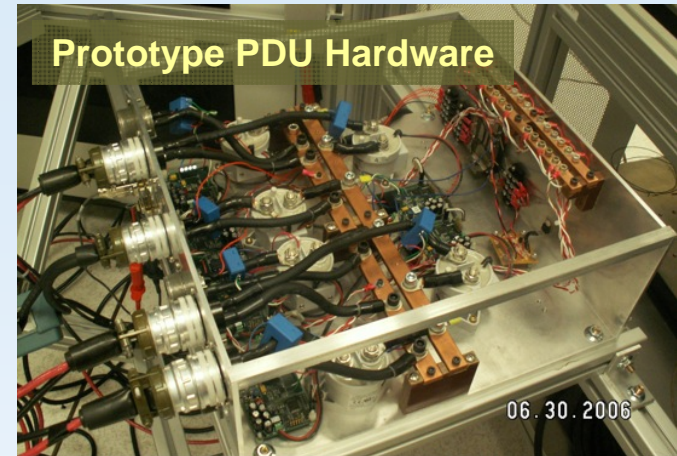
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Proof-of-Concept Design Studies

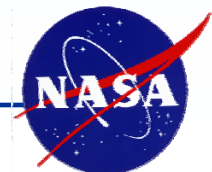
- Objectives
 - Demonstrate proof-of-concept for ***analytical redundancy-based*** data qualification methods using test-beds relevant to Upper Stage Subsystems
 - Conduct studies to characterize real-time (onboard) implementation and execution
 - Simulate sensor failures in hardware and detect in real-time
- Performance Metrics
 - Identifies known sensor failures with
 - No false alarms
 - Near-zero missed detections
 - Deterministic Real-time Execution



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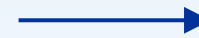
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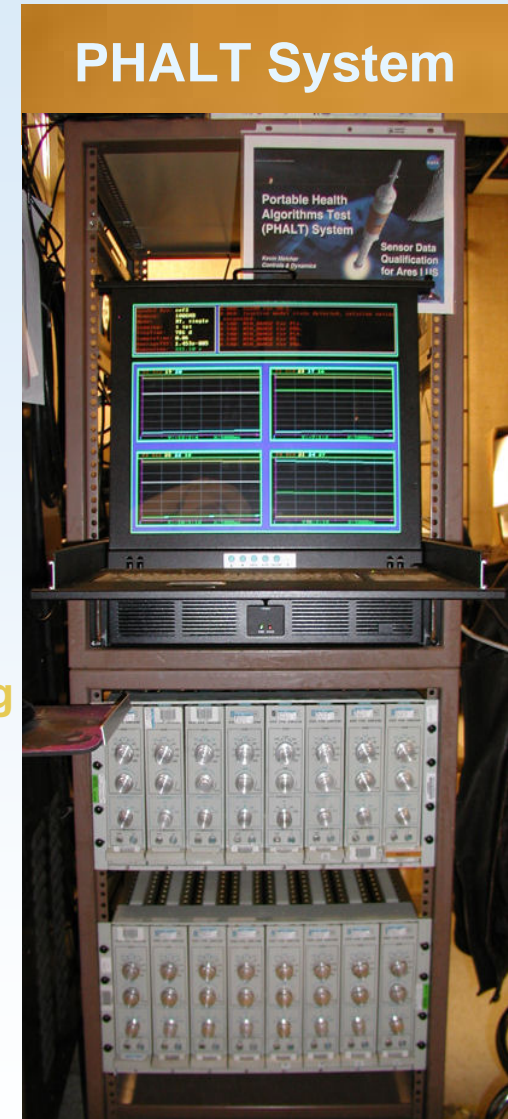
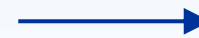
Portable Health Algorithms Test (PHALT) System

- The PHALT System was developed for use in rapid prototyping and testing of diagnostic algorithms
 - **Portable:** Laptop (development platform) and industrial, rack-mount PC (real-time target) provide portability to support on-the-road demonstrations and real-time testing
 - **Health Algorithms**
 - Currently limited to data validation
 - Capability to add a variety of diagnostic & prognostic health management algorithms
 - **Test**
 - Matlab/Simulink xPC software provides capability for rapid prototyping and seamless generation of real-time applications.
 - Industrial PC with real-time I/O supports real-time testing of algorithms with broad spectrum of available test rigs.

Real-time
Target with
GUI & I/O



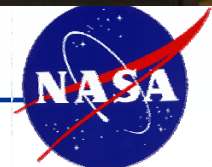
Anti-aliasing
Filters



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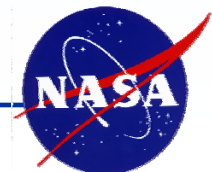
Conclusion

- GRC developing key technologies for access to space propulsion system ISHM
 - Systematic Sensor Selection Strategy (S4) to determine “optimal” sensor suite for Fault Detection and Isolation
 - Sensor Data Qualification System (SDQS) to ensure that the FDI is based on validated data
- S4 and SDQS technologies being applied to NASA Exploration System programs
 - S4 to be used for making sensor selection decisions for J-2X
 - SDQS to be part of Ares I Upper Stage Abort System
- NASA interested in further technology maturation and application opportunities

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Overview:

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Sensor Selection:

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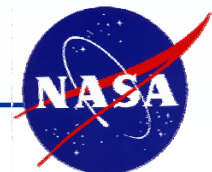
CDB Overview

- **Mission**
 - Research, develop and verify aerospace propulsion dynamic modeling, health management, control design and implementation technologies that provide advancements in performance, safety, environmental compatibility, reliability and durability
 - Facilitate technology insertion into the mainstream aeropropulsion community
- **Capabilities**
 - 20+ engineers and scientists - most with advanced degrees and extensive experience in aeropropulsion controls related fields
 - Extensive computer-aided control design and evaluation facilities including real-time and man-in-the-loop simulation facility
 - Strong working relationship with controls technology groups in the aerospace propulsion industry, academia and other agencies

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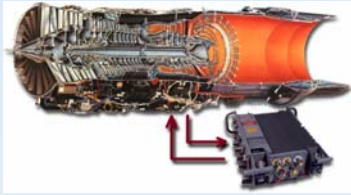
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RHC – Controls and Dynamics Branch Overview

Propulsion Controls



Active Flow Control

- High bandwidth actuation

Active Combustion Control

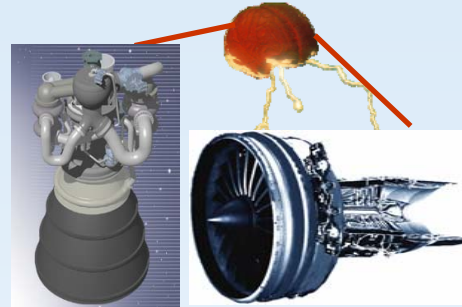
- Modeling and control of Thermo-acoustic Instability

Advanced Control Logic

- Fast engine response for adverse conditions
- Engine life and performance trade-off
- Mitigation of deterioration effects on performance

Advanced Control Architectures

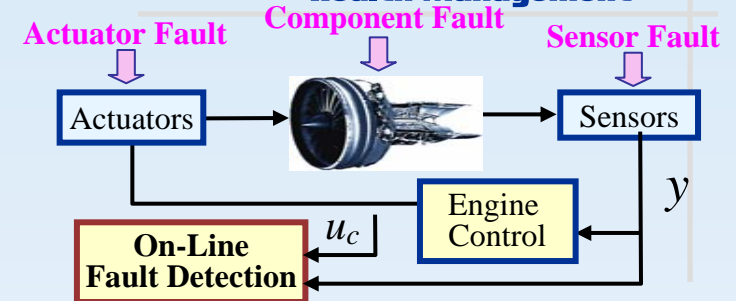
- Distributed Engine Control



Aerospace Propulsion Control and Health Management Technologies

- Active Component Control and Intelligent Control for Turbomachinery based Aircraft Propulsion Systems
- On-line Fault Diagnostics of Aircraft Engines and Space Propulsion Systems
- Advanced Unsteady Combustion Systems for Propulsion
- Robotics Control and Software

Health Management



Sensor Selection

- Optimal sensor suites for reliable fault diagnostics

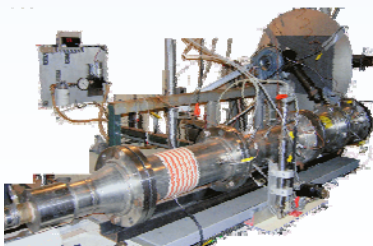
Data Validation

- Analytical redundancy based data qualification methods
- Real-time application validation

Model-Based Diagnostics

- Advanced estimation techniques for gas path health monitoring
- Integrated trending and on-line diagnostics for reliable fault detection and isolation

Unsteady Combustion Systems



Advanced Propulsion Concepts

- Pulse Detonation Engine performance modeling
- Pressure Gain combustion systems for turbomachinery

Robotic Control and Software

- Test-bed for rapid development and evaluation of autonomous cooperative control algorithms
- Lunar rover vision system software

Robotic Control



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